High Yield CIS Production - Progress & Perspectives

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ABSTRACT

Outstanding progress has been made in the scale-up of high performance CIS thin film solar electric modules. Cumulative production for 2002 exceeded 1 MW; about twice the production rate for 2001. Line yield has increased from about 60% in 2000 to about 85% in 2002. Electrical performance has proven to be predictable with aperture efficiencies over 10%. These major accomplishment supports attractive cost projections for CIS. This paper will discuss Shell Solar Industries's (SSI's) status and plans for commercialization of CIS-based thin-film PV with emphasis on line yield and will present an example of how barcode scribing has improved both productivity and yield.

1. Introduction

SSI produces commercial large-area multinary $Cu(In,Ga)(Se,S)_2$ (CIS) modules. SSI's approach to the development of CIS is to demonstrate at successive levels of production the prerequisites for commitment to large-scale commercialization – a predictable process, high efficiency, long-term outdoor stability, and attractive cost projections on cost per watt basis [1]. Although production at SSI is at an early stage relative to the thin-film goals and objectives defined by the DOE and NREL for the years 2010 and 2020 [2], SSI approaches to production R&D are in harmony with these DOE goals. SSI is presently developing large-scale production processes and working to master and rigorously demonstrate these processes for the full process sequence anticipated for use in large-scale production.

CIS circuits are fabricated monolithically; cell interconnection is accomplished as part of the process sequence by alternately depositing layers in the cell structure and patterning the layers using laser and mechanical scribing. The process starts with sodalime window glass. A Mo base electrode is sputtered onto the substrate. CIS formation is accomplished by heating copper/gallium alloy and indium precursors in H_2Se and H_2S to form the CIS absorber. A very thin coating of cadmium sulfide is deposited by chemical bath deposition and a transparent contact is made by chemical vapor deposition of zinc oxide. EVA is used to laminate the circuit plate to a tempered cover glass and to a Tedlar/Polyester/Al/Tedlar (TPAT) backsheet that provides a hermetic seal. Aluminum extrusions are used as frames for the modules. SSI has adopted Statistical Process Control (SPC) methodologies because SPC was developed to rigorously quantify process reproducibility and process capability; the essence of SPC is predictability. Application of these SPC methodologies have led to excellent progress toward demonstrating that CIS meets the prerequisites for a commitment to large-scale commercialization for all of these process steps at higher production rates.

This paper will review SSI accomplishments, status and plans, discuss process development for improved yield, present an example of how barcode scribing has increased productivity and yield, and present an industrial perspective on current and future CIS commercialization.

2. Status and Plans

NREL has confirmed a champion 12.8 percent aperture area conversion efficiency for a large area ($3626\ cm^2$) CIS module. The aperture area for this champion module was defined by taping off the approximately 1 cm inactive boarder surrounding the monolithically integrated CIS circuit plate in a ST40, 40 W, production module. Other than definition of the aperture area, this module is simply a module from the upper end of the production distribution for standard modules. Figure 1 is the production distribution for approximately sixteen thousand ~1x4 ft. laminates produced during 2002. The average efficiency of this distribution is 10.8%. A Normal distribution fit to the main portion of the distribution yields a full width of 0.66%; the full width of the distribution is about 12% of the average. Over 88% of this production output is over 10% efficiency.

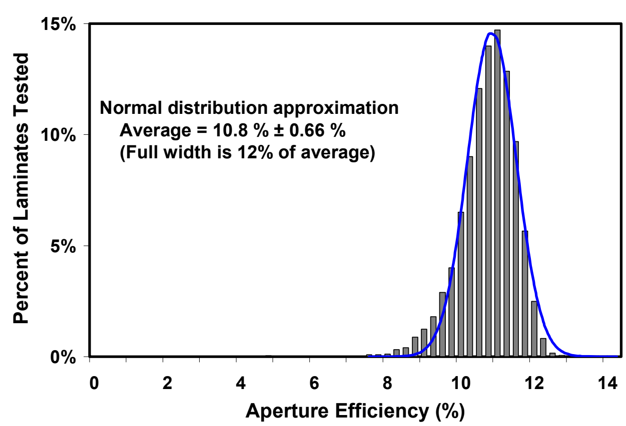

Figure 1. Production distribution for 1x4 ft. laminates produced during 2002.

These champion efficiency and production distribution results are particularly notable since they were achieved along with a cumulative production for

2002 of over 1 MW; about twice the production rate for 2001. Historical production rates, plans for further scale-up through 2008 in existing facilities and cost projections are charted in Figure 2.

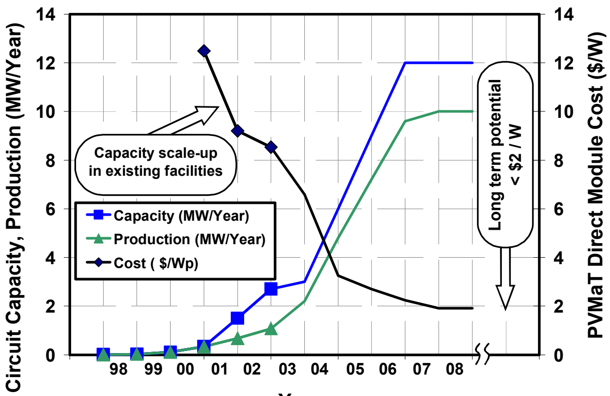

Figure 2. Historical production rates, plans and cost projections

Production rates are projected to increases by an order of magnitude to about 10MW per year. Cost projections during this timeframe for direct costs, based on PV Manufacturing R&D program criteria for direct costs and assuming scale-up constrained to existing facilities, indicate reductions from about $8 to about $2 per Watt. Long term, direct costs for CIS are expected to be less than $2 per Watt.

Dramatic increases in CIS line yield have been demonstrated. Line yield is defined as the ratio of two areas – the area of product produced divided by the area of glass started through the production line. This is total yield including both electrical yield and mechanical yield through all processing required to produce products. Line yield has increased from about 60% in 2000 to about 85% in 2002. Process development guided by SPC approaches for all process steps was required to achieve this high yield. This major accomplishment supports attractive cost projections for CIS.

One way NREL supports SSI is through long term testing of arrays and individual modules at the NREL Outdoor Test Facility (OTF). Long-term outdoor stability has been demonstrated at NREL where ~30x30 cm and ~30x120 cm modules with multiple prototype package designs have undergone testing for over thirteen years. FM and UL approval has been obtained for the ST series of products and the performance of the ST family of CIS thin-film products is backed by a 10-year warrantee.

SSI is now developing a “glass/glass” package that eliminates the TPAT backsheet for decreased cost, simplification of the package and decreased operating temperature. Figure 3 is a sketch of the present production package and the proposed glass/glass package. Simplification of the package should increase yield. Decreasing the operating temperature will lead to higher efficiency for modules in the field.

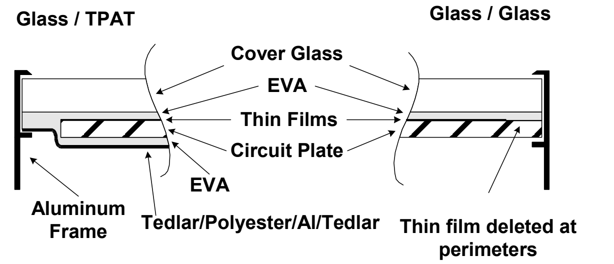

Figure 3. Present and future (glass/glass) package designs.

No detectable humidity ingress occurs during damp heat testing of the current SSI products with a TPAT backsheet where damp heat testing refers to an exposure for 1000 hour at 85°C and 85% relative humidity. The new glass/glass package is required to pass accelerated environmental tests such as this damp heat test; however, this will require additional moisture protection. Figure 4 is a photo of the edge of a glass/glass module where the interconnect patterning for monolithic integration is visible as vertical lines above the ruler.

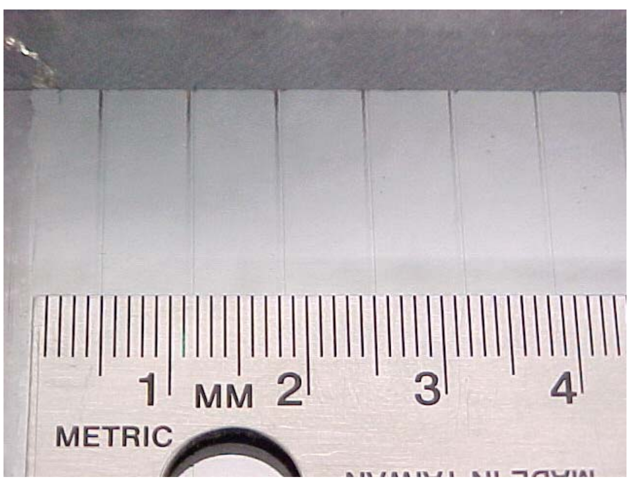

Figure 4. Signature of Moisture Ingress for a prototype glass/glass package.

Darkening and broadening of the interconnects at the edge of the circuit plate is observed for glass/glass packages after damp heat testing and has been found to be an indicator of power loss due to moisture ingress. This is not observed for the glass/glass package after the same thermal exposure but without high humidity. Similarly, the darkening and broadening of the interconnects is not observed for production products, that employ a TPAT backsheet, after the same thermal exposure with or without high humidity. Edge seal and barrier coatings to block humidity ingress are being explored at SSI and in collaboration with a new NREL sponsored National Thin-Film PV Module Reliability Team.

3. High Yield Production

Goals for SSI's Thin Film Photovoltaics Partnership Program (TFPPP) subcontract with NREL are to accelerate the progress of thin film solar cell and module development as well as to address mid and long-term research and development issues by achieving aggressive interim goals for thin film module efficiencies, cell and module processing, cell and module reliability, and in the technology base that supports these key areas [3]. Although yield improvements are not specifically mentioned, yield is as important as the previously mentioned advances in efficiency and production rate. High yield is implicitly included in the prerequisites for commitment to large scale production through the requirements for a predictable process and attractive cost projections.

Figure 5 illustrates yield improvements over the last three years. No one major process improvement was responsible for demonstrated yield improvements. Instead, these advancements were due to continuous improvement of all process. Judicious application of manufacturing engineering disciplines such as SPC, analysis of variation and design of experiments led to a clear definition of near term yield issues. The dramatic improvements in monthly yield through this timeframe were the result of improving production protocols and addressing disparate special causes for process variation.

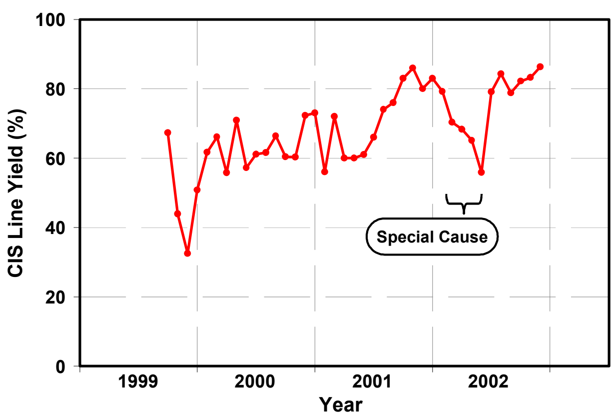

Figure 5. CIS line yield.

Significant improvements were made by developing protocols and procedures for sun soaking modules prior to final testing. Yield improvements as the result of process development included:

- Decreased breakage at multiple process steps related to handling and process definition
- Elimination of shunting along the laser scribe in the Mo base electrode related to both the Mo deposition and laser patterning processes
- Decreased loss due to equipment failures by improving control systems and production procedures
- Decreased peeling related to glass cleaning, precursor deposition, the reaction process, reactor uniformity, and ZnO deposition
- Decreased loss of process runs by improving infrastructure for higher capacity and yield

These yield improvements were obtained through repeated cycles of learning. For example, the drop in yield through the first half of 2002 was due to peeling. This was found to be due to setup and wear issues for a glass washer; issues that are obvious and trivial in hindsight. Finding and addressing this special cause lead to the immediate and permanent return to high yield.

Further yield improvements are anticipated such as:

- Reduced breakage by edging glass or improving glass scribing quality
- Reduced losses by implementation of a glass/glass module package which is less complex and eliminates a glass trimming step
- Reduction of losses related to equipment failures by improving equipment control systems and production procedures

4. Example – Barcode Scribing Increases Yield

The objectives of SSI's PV Manufacturing R&D subcontract with NREL do not directly address yield improvements; however, yield improvements have been obtained through process development for equipment developed and implemented for this subcontract [4]. The objective of this subcontract is to continue the advancement of SSI's CIS technology through specification and procurement of equipment, process feedback and integrated manufacturing. SSI defined the requirements and procured laser barcode scribing and barcode reading equipment with the goals of increasing capacity by improving productivity and providing high quality data for integrated manufacturing infrastructure tasks. Figure 6 illustrates the corner of a circuit plate with both a readable serial number for humans and a 2-dimensional barcode for machines.

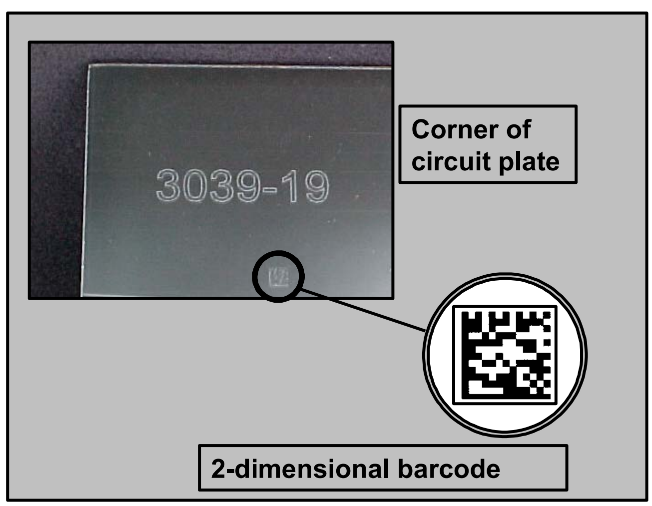

Figure 6. Laser Barcode.

Barcode scribing has improved production productivity; bar code reading has proven to be easier, faster and more accurate than manual reading of hand scribed serial numbers. Process data ambiguity due to duplicate and missing serial number data has been practically eliminated. Engineering productivity has also improved since the frustrating and time consuming task of reconciling data with erroneously logged serial numbers has been practically eliminated. Also, process development work for the TFPPP subcontract has demonstrated that reduced breakage is an additional benefit of bar codes scribing. A study of yield loss due to breakage during the absorber formation process demonstrated that breakage associated with hand scribed serial numbers was one of the major causes of breakage. The use of laser scribed bar codes has reduced this kind of breakage by 88%.

5. Summary and Perspectives

Outstanding progress has been made in the initial commercialization of high performance thin film CIS technology. Further device and production R&D can lead to higher efficiencies, lower cost, and longer product lifetime. Prerequisites for commitment to large-scale commercialization have been demonstrated at successive levels of CIS production. Remaining R&D challenges are to scale the processes to even larger areas, to reach higher production capacity, to demonstrate in-service durability over longer times, and to advance the fundamental understanding of CIS-based materials and devices with the goal of improvements for future products. SSI's thin-film CIS technology is poised to make very significant contributions to DOE/NREL/NCPV long-term goals - higher volume, lower cost commercial products.

REFERENCES

[1] R. Gay, “Prerequisites to Manufacturing Thin-film Photovoltaics”, Thin Film Photovoltaic Symposium, IEC, May 1997. Published in Progress in Photovoltaics: Research and Applications, 5 (1997) pp. 337-343.

[2] Photovoltaics--Energy for the New Millennium: The National Photovoltaics Program Plan, 2000-2004. (2000). 22 pp.; NICH Report No. BR-520-25847; DOE/GO-10099-940.

[3] “PROCESS R&D FOR CIS-BASED THIN-FILM PV”, NREL subcontract ZDJ-2-30630-16

[4] Integrated CIS Thin-Film Manufacturing Infrastructure”, NREL subcontract # NDO-1-30628-06